Effect of Displacement Increment on Fracture Toughness (J_{Ic}) of HSLA Steel

THESIS SUBMITTED FOR THE DEGREE OF

Master of Technology

In

MECHANICAL ENGINEERING

By

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NIT Rourkela, Odisha

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CERTIFICATE

This is to certify that the thesis entitled, **"Effect of displacement increment on Fracture Toughness (J_{Ic}) of HSLA Steel"** submitted by **Prasant Kumar Swain** in partial fulfillment of the requirements for the award of Master of Technology Degree in **Mechanical Engineering** (specialization of **M/c Design & Analysis)** at National Institute of Technology, Rourkela, Odisha (INDIA) is an authentic work carried out by him under our supervision and guidance. To the best of our knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any degree or diploma.

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Prasant Kumar Swain
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Abstract

Fracture toughness of low strength tough materials are provided by the *J*-integral and expresses as J_{Ic}. The resistance curve procedure, specified in ASTM E1820, is mostly used to obtain the fracture toughness, since it is a single specimen test, unlike the basic procedure which requires multiple specimens. In this method the specimen undergoes loading, unloading and reloading process repeatedly. The spacing between unload/reload sequence is known as displacement interval or displacement increment. ASTM E1820, specifies the maximum limit of displacement interval/displacement increment between each unload/reload sequence (0.01 times of the remaining ligament). However, it has been observed from experiments that there is variation of J_{Ic} values at lower values of displacement interval/displacement increment. Hence in this work the effect of displacement increment on J_{Ic} of HSLA (High Strength Low Alloy) steel has been studied through experimental investigations and an attempt has been made to obtain the range of displacement increment where the variation of J_{Ic} values is within acceptable limit. Another two parameters which affect the value of fracture toughness is *a/W* (crack length to specimen thickness) ratio and loading rates/strain rates. It is reported that there is no significant influence of loading rates on fracture toughness. Therefore in this investigation fracture toughness was measured with varying *a/W* ratio and displacement increment. The tests were carried out with side-grooved full C(T) specimen, following ASTM-E1820. The resistance curve procedure which utilizes unloading compliance (UC) method, is used to evaluate the fracture toughness.

Keywords: fracture toughness, C(T) specimen, J_R curve, *J*-integral, *b/W* ratio, displacement increment, loading rate

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Nomenclature

B	Specimen thickness (mm)
Be	Effective thickness (mm)
B_N	Net specimen thickness (mm)
W	Specimen width (mm)
a_o	Original crack size (mm)
a_{oq}	Provisional crack length (mm)
a_n	Notch length (mm)
a_i	Crack length at i^{th} loop
Δa	Crack extension (mm)
b_o	Original remaining ligament length (mm)
K_{max}	Maximum stress intensity factor $\left(MPa\sqrt{m}\right)$
K_{min}	Minimum stress intensity factor $\left(MPa\sqrt{m}\right)$
ΔK	Stress intensity factor range $\left(MPa\sqrt{m}\right)$
R	Stress ratio ($\sigma_{\min} / \sigma_{\max}$)
σ_{YS}	Yield stress (MPa)
σ_{TS}	Ultimate Strength (Mpa)
σ_Y	Flow stress; $(\sigma_{TS}+\sigma_{YS})/2$(MPa)
$\Delta\sigma$	Stress range (MPa)
E	Young's modulus of elasticity (MPa)

P_{max}	Maximum load of constant amplitude load cycle (N)
J_Q	Provisional JIC fracture toughness
J_{Ic}	Critical path independent contour integral
K_{Ic}	Critical crack tip stress intensity factor

Chapter-1

INTRODUCTION

1.1 Background

For large complex structures like bridges, ships, air crafts, the possibility to have a crack/flaw is more. When there is a pre-existing crack, fracture mechanics is used to establish the allowable stress level which the material can withstand to avoid fracture. So study of fracture mechanics is important in modern era. Fracture mechanics is based on the assumption that there exists a crack in a work component. The crack may be man-made such as hole, notch, a slot, a corner. The crack may exist within the component due to manufacturing defects like slag inclusion, cracks in a weld-ment or heat affected zone, due to irregular cooling and presence of foreign particles [1].

1.2 Objective

In fracture mechanics, attempts are made to predict and avoid the failure due to fatigue loading. The objective is to know how much maximum stress it takes for a crack to grow or what can be the maximum size of the crack in a component to withstand a particular stress. Thus the word fracture toughness comes into the picture. Fracture toughness is the material's ability to resist growth of a crack. Quite often the difficultly arises in determining the fracture toughness of a material.

Chapter-2

LITERATURE REVIEW

2.1. Fracture Mechanics

Fracture mechanics is the field of mechanics which deals with the study of the propagation of cracks in materials. Fracture mechanics is based on the inherent assumption that there already exists a crack in an engineering component or structure. The crack may be either man-made as a key-hole, a groove, a notch or a slot, etc. or it may exist within a component due to manufacturing defects like slag or impurities inclusion, cracks in a weld-ment or heat affected zones due to irregular cooling and existence of foreign particles. A crack may be nucleated and start growing during the service of the machine elements or structure [2].

2.2. Classification of Fracture Mechanics

Fracture mechanics is classified into two: 1. Linear Elastic Fracture mechanics 2. Elastic Plastic fracture mechanics.

2.2.1. Linear Elastic Fracture Mechanics (LEFM)

The assumptions on which the Linear Elastic Fracture Mechanics (LEFM) is based, are that the material is isotropic and linear elastic. When there is inelastic deformation near the crack-tip, and the size of plastic zone is very small compared to the size of the crack (what we called small-scale yielding), LEFM can also be applied effectively. In LEFM the stress field near the crack tip is calculated using the theory of elasticity. When the stresses near the crack tip exceed the material fracture toughness, the crack will grow. The fracture toughness in LEFM is characterized by "Stress intensity factor (K)".

2.2.2. Elastic Plastic Fracture Mechanics (EPFM)

Elastic Plastic Fracture Mechanics (EPFM) assumes the material as isotropic and deformation occurred during fatigue loading is elastic-plastic. Elastic Plastic Fracture Mechanics (EPFM) applies when large regions of the material around the crack tip are subject to plastic deformation. In EPFM the strain energy fields or opening displacement near the crack tip is calculated and when the energy of opening exceeds the critical value, the crack will grow. The fracture toughness in EPFM is characterized by *J*-integral (proposed by Rice) or Crack Tip Opening Displacement (CTOD) (suggested by Well).

By idealizing the elastic-plastic deformation as nonlinear-elastic, the base of fracture mechanics was extended by Rice beyond the limitations of LEFM.

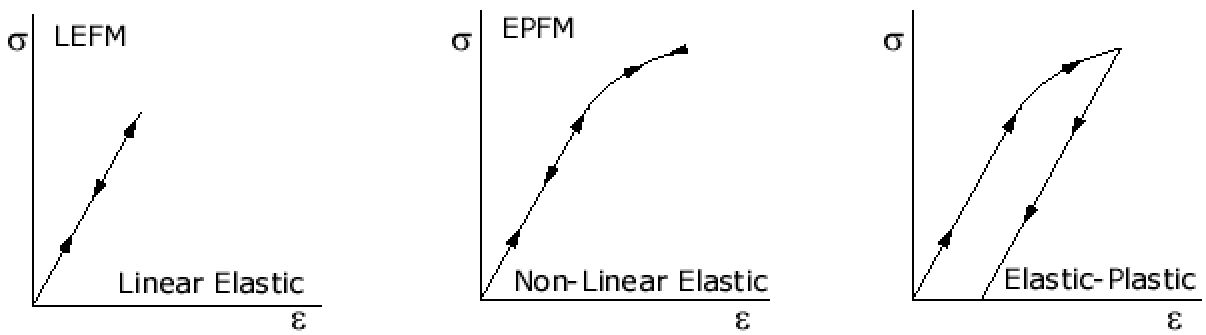


Fig 2.1 Stress strain curve for linear elastic / non-linear elastic / elastic plastic material

2.3 Fracture Toughness

Fracture toughness is a material property which describes the ability of the material containing a crack to resist further growth of crack. It is a very important material property since the occurrence of flaws can’t be avoided completely in the processing, fabrication, or service of a material/component. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof. Since engineers can never be totally sure that a material is flaw free, it is common practice to assume that a flaw of some chosen size is present and use the fracture mechanics approach to design critical components.

2.4 Measurement of Fracture toughness:

Several terms/parameters which describes the fracture toughness of materials, are stress intensity factor (K_{IC}), J-integral (J_{IC}), crack-tip opening displacement (CTOD) and crack-tip opening angle (CTOA).

When a material behaves in a linear elastic manner, prior to failure, such that the plastic zone is small compared to the specimen dimension, the stress intensity factor (K) is the appropriate fracture parameter. It was proposed by Irwin in 1957.

The J-integral is a path-independent contour integral, which is equal to the energy release rate in a nonlinear elastic body that contains a crack. It was proposed by J Rice in 1968, by idealizing the elastic-plastic deformation as nonlinear elastic. It characterizes the stress intensity of elastic-plastic zone ahead of crack-tip and symbolizes elastic-plastic fracture mechanics (EPFM).

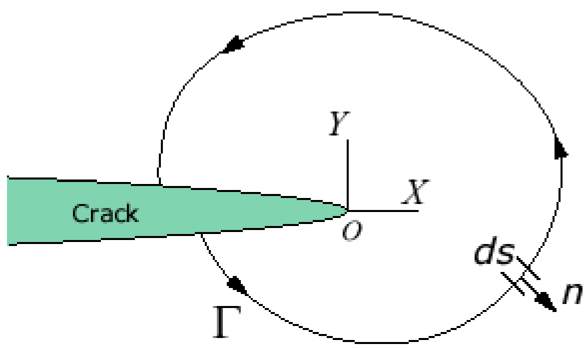
CTOD concept was proposed by Wells to serve as an engineering fracture parameter, and can be equivalently used as K or J-integral. Wells noticed that plastic deformation makes an initially sharp crack, blunt, and the degree of crack blunting increased in proportion to the toughness of the material. Hence the opening at the crack tip can be used as a measure of fracture toughness.

The CTOA parameter is used in recent decades to describe the fracture behavior of a stable crack extension for thin walled materials [3].

2.5 *J*-integral

The *J*-integral concept was proposed by Rice, to characterize the fracture behavior of low strength materials, undergoing large scale plasticity. By idealizing the elastic-plastic behavior as non-linear elastic behavior, Rice applied deformation plasticity (i.e., non-linear elasticity) theory to the analysis of a crack. The mathematical expression is:

$$J = \int_{\Gamma} w dy - T_i \frac{\partial u_i}{\partial x} ds$$



where $w = \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij}$ is the strain energy density, $T_i = \sigma_{ij} n_j$ is the traction vector, Γ is an arbitrary contour around the tip of the crack, *n* is the unit vector normal to Γ, σ, ε, and *u* are the stress, strain, and displacement field, respectively.

J. R. Rice showed that the J integral is a path-independent line integral and it represents the strain energy release rate per unit surface area of elastic-plastic materials i.e.

$$J \equiv -\frac{d\Pi}{dA}$$

where $\Pi = U - W$ is the potential energy, the strain energy *U* stored in the body minus the work *W* done by external forces and *A* is the crack area.

J_{Ic} can be used as a toughness value at the initiation of crack tearing from a sharp fatigue crack in metallic materials.

2.6 Types of loading

There are three type of loading an engineering component is supposed to be acted upon. Those are Mode-I, Mode-II and Mode-III. For different modes the fracture toughness is different. The different mode of loading is shown in Fig 2.3 below.

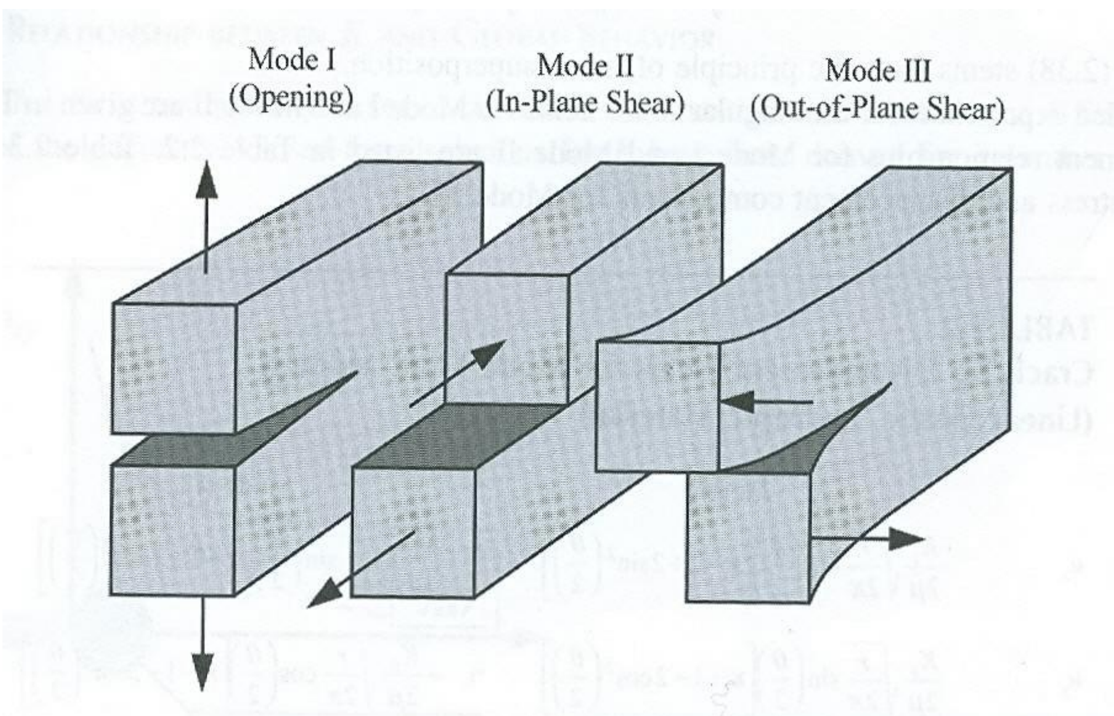


Fig 2.2 Three modes of loading

2.7 Influence of various geometric factors on J_{Ic}

Though the fracture toughness is a material property, there are few geometric parameters, which influence the value of Fracture toughness. The findings from the literature review are listed below:

The variation of the initiation fracture toughness, J_{Ic}, with increasing specimen thickness shows that the J_{Ic} is more or less insensitive to increasing thickness. This is true especially at low *a/W* ratio. However, at high slight increase in J_{Ic} is noticed with increasing value of *a/W* ratio [4].

The study of influence of strain rate on fracture toughness of SS316L has been carried out and found that at ambient temperature there is no significant influence of the loading rate/strain rate on the value of J_{Ic} [5].

Author concluded that the fracture-initiation toughness of the aluminum7017-T73 alloy remained constant regardless of the velocity (loading rate/strain rate) at which the load was applied [6].

With a ductile fracture mechanism of void nucleation, growth and coalescence, the fracture toughness parameters, J_{Ic} is nearly independent of loading rate for a sufficiently low loading rates and then increase rapidly at higher loading rates [7].

For a fixed specimen width, toughness decreases and ductile-brittle transition occurs with increasing *a/W* [8].

The initiation fracture toughness (J_{Ic}) is more for shallow crack and less for deep cracks [9]. The variation of fracture toughness with in-plane constraints are shown in the Figure 2.3.

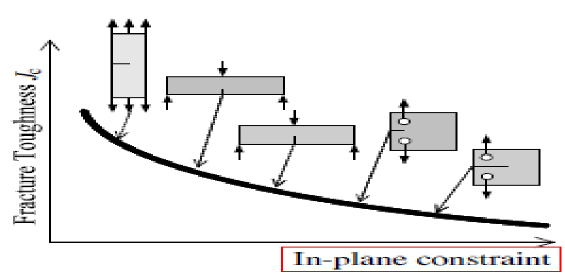


Fig 2.3 fracture toughness vs in-plane constraints

Chapter 3

MATERIAL PROPERTIES AND SPECIMEN PREPARATION

3.1 Material and it's composition

The material taken for the investigation is HSLA (High Strength Low Alloy) steel supplied by RSP Rourkela. HSLA steels are important structure materials for their good strength to weight ratio, better corrosion resistance than carbon steel, good weldability. The material is suitable for automobile industry, structures (bridges, roller coaster) and hulls of navy vessels. The composition of the material is provided in Table No. 3.1 below:

Table 3.1 Chemical composition of HSLA steel

C	Mn	Si	P	S	Al	V	Nb	Mo	Fe
0.2	1.27	0.25	0.021	0.014	0.05	0.001	0.005	0.001	Balance

Thickness of the supplied plate=12.3mm

3.2 Specimen Preparation

Full Compact Tension (CT) specimen with reduced thickness specimens were fabricated from the supplied following the guidelines of ASTM E 1820 [10] maintain LT-orientation. Configuration of a specimen is shown in **Figure-3.1**. The designated dimensions of the specimens were; thickness (B) 12mm, width (W) 51mm and machine notch length (a_n) 9.5mm. To avoid deflection of crack during course of growth, grooves were created on both sides of the specimen. The side grooving was milled maintain a notch angle 60° and depth of approximately 1.2 mm on each side of the specimen. This was done to enhance the stress tri-axiality at the crack tip and net thickness of specimen is 9.4mm. The dimensions of the specimens used in this investigation are as shown in Fig-3.2 [11].

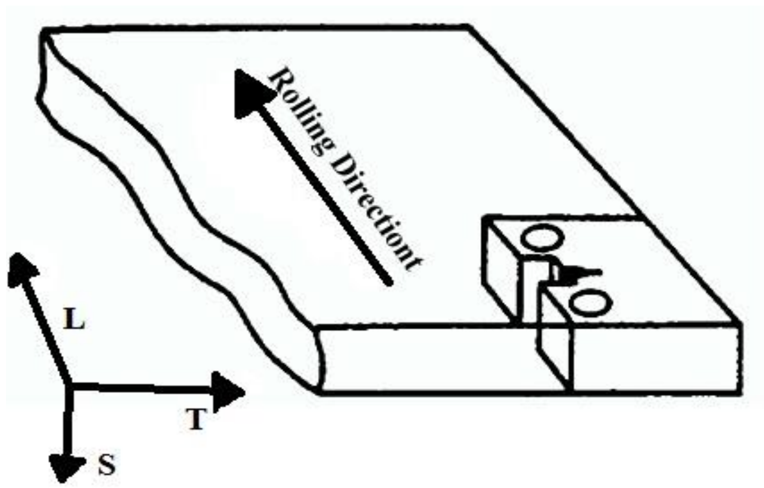


Fig 3.1 Configuration of the fabricated specimen

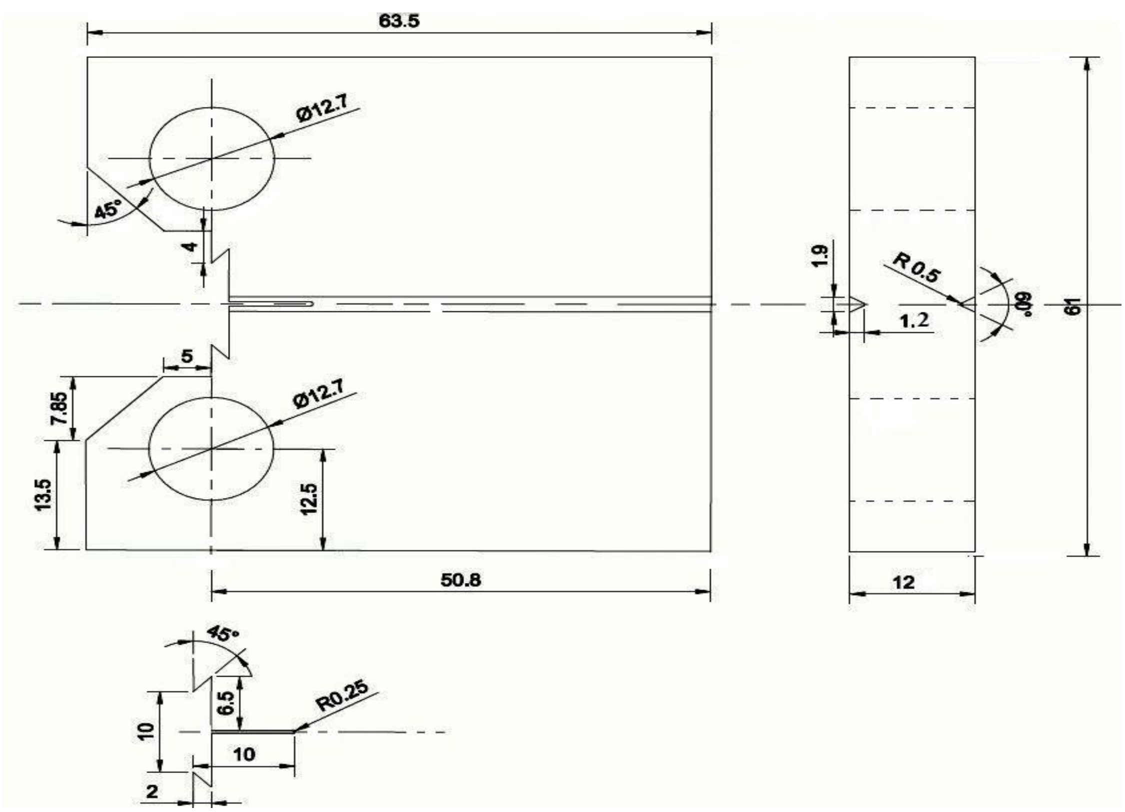


Fig 3.2 Dimension details of the C(T) specimen (all dimension are in mm)

Table 3.2 Detailed dimension of C(T) specimen tested

Specimen Sr. No	**Specimen Dimension**			
	Width (W) (in mm)	**Notch Length(a_N) (in mm)**	**Thickness (B) (in mm)**	**Net Thickness(B_N) (in mm)**
J_{Ic}-1	51	9.5	11.95	9.35
J_{Ic}-2	51	9.5	11.9	9.4
J_{Ic}-3	51	9.5	11.9	9.4
J_{Ic}-4	51	9.5	11.9	9.4
J_{Ic}-5	51	9.5	11.9	9.4
J_{Ic}-6	51	9.5	11.95	9.4
J_{Ic}-7	51	9.5	11.95	9.3
J_{Ic}-8	51	9.5	11.95	9.3
J_{Ic}-9	51	9.5	11.95	9.4

Chapter-4

EXPERIMENTAL SET-UP, PROCEDURE & DATA ANALYSIS

4.1 Experimental set-up details:

Experiment was conducted using closed loop 100 kN load *BiSS* servo-hydraulic universal testing machine.

Fig 4.1 100kN Universal Testing machine

4.2 Test Procedure

All the specimens were pre-cracked at constant ΔK condition maintaining ΔK =19.99 MPa$\sqrt{}$m, stress ratio R=0.3 and test frequency 5Hz. Variable amplitude crack propagation (VAFCP) fatigue software was used during test. The precracking was done for a/W ratio of 0.5, 0.55 and 0.6 (three specimens at each a/W ratio). Purpose of pre-cracking was for getting sharp initial cracks.

J_{Ic} test of pre-cracked specimen were carried out using *J-R Test-2370* based application software with various displacement increment (0.03, 0.05, 0.06, 0.075, 0.1). This is done by carrying out a series of sequential unloading and reloading during the test. The loads versus displacement plots generated by the machine are provided in Fig 4.2 to 4.10.

The analysis are done using unloading compliance technique. In this method the crack lengths are determined from elastic unloading compliance measurements. All the experiments were conducted with Mode-I loading and at ambient temperature.

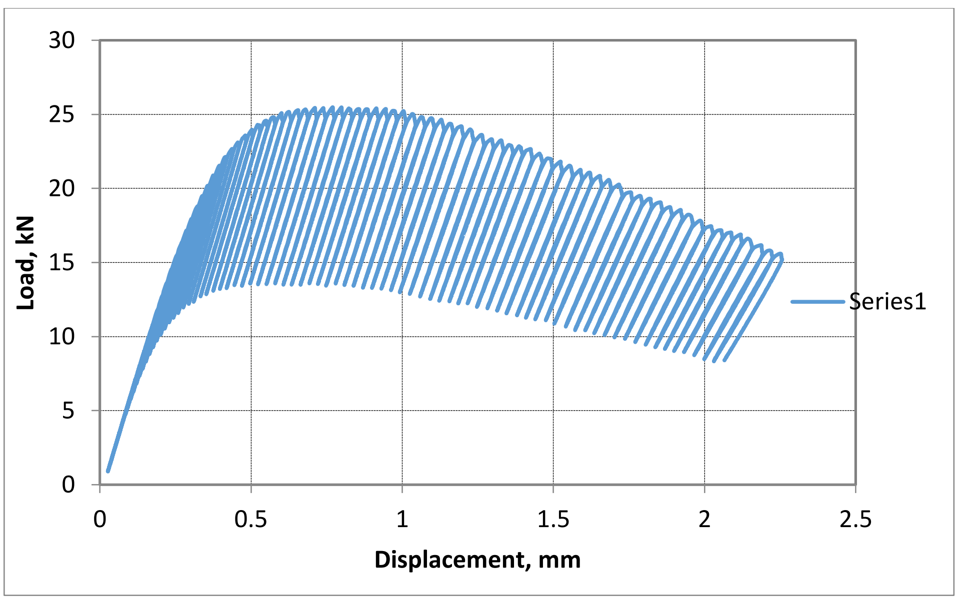


Fig 4.2 Load vs displacement (a/W=0.5 and displacement increment=0.03mm/cycle)

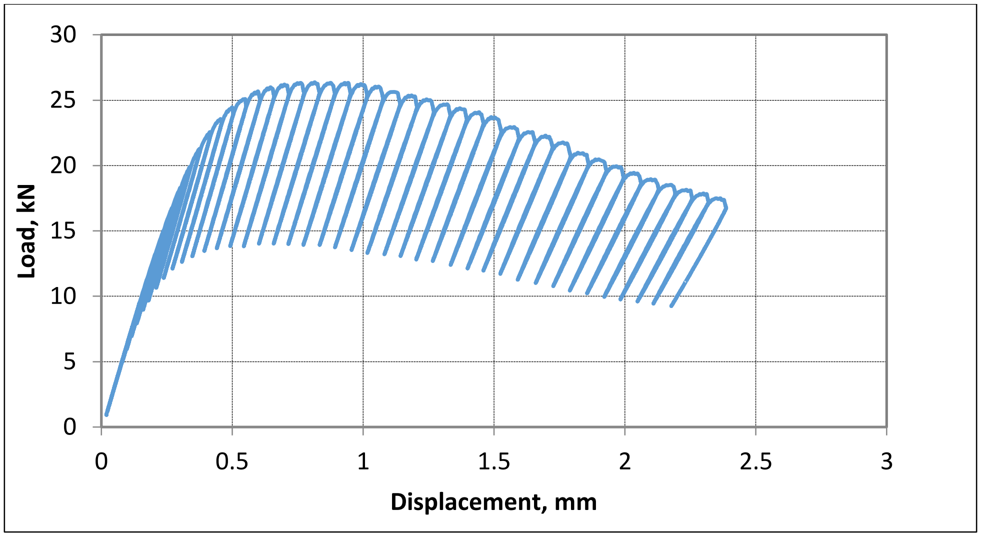


Fig 4.3 Load vs displacement (a/W=0.5 and displacement increment=0.06mm/cycle)

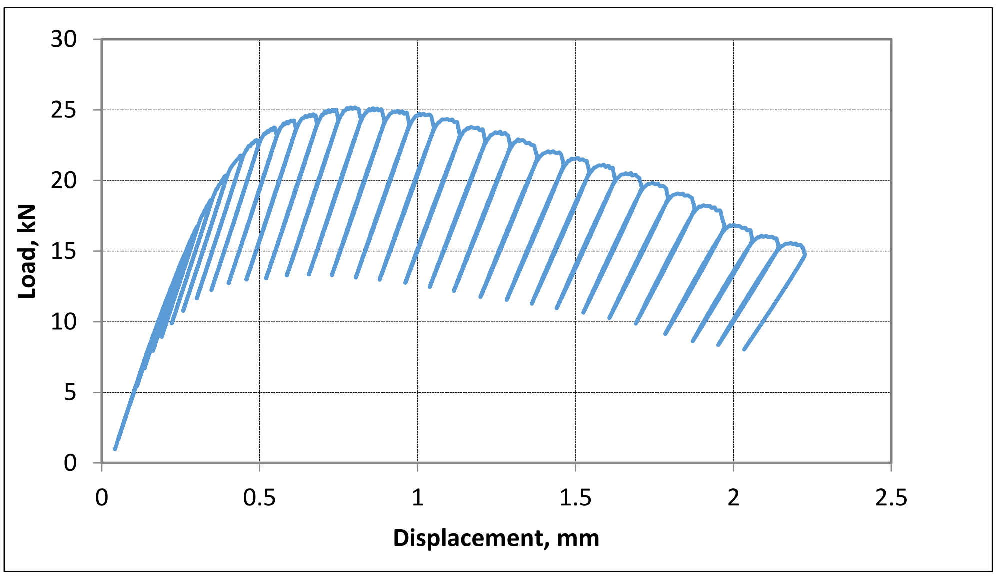


Fig 4.4 Load vs displacement (a/W=0.5 and displacement increment=0.075mm/cycle)

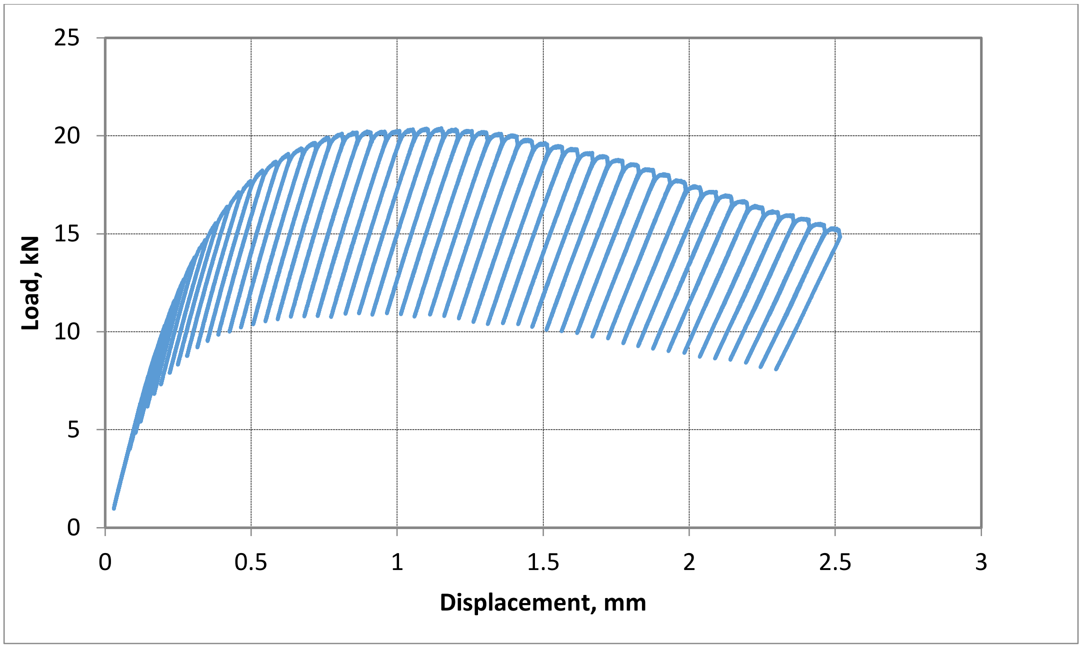


Fig 4.5 Load vs displacement (a/W=0.55and displacement increment=0.05mm/cycle)

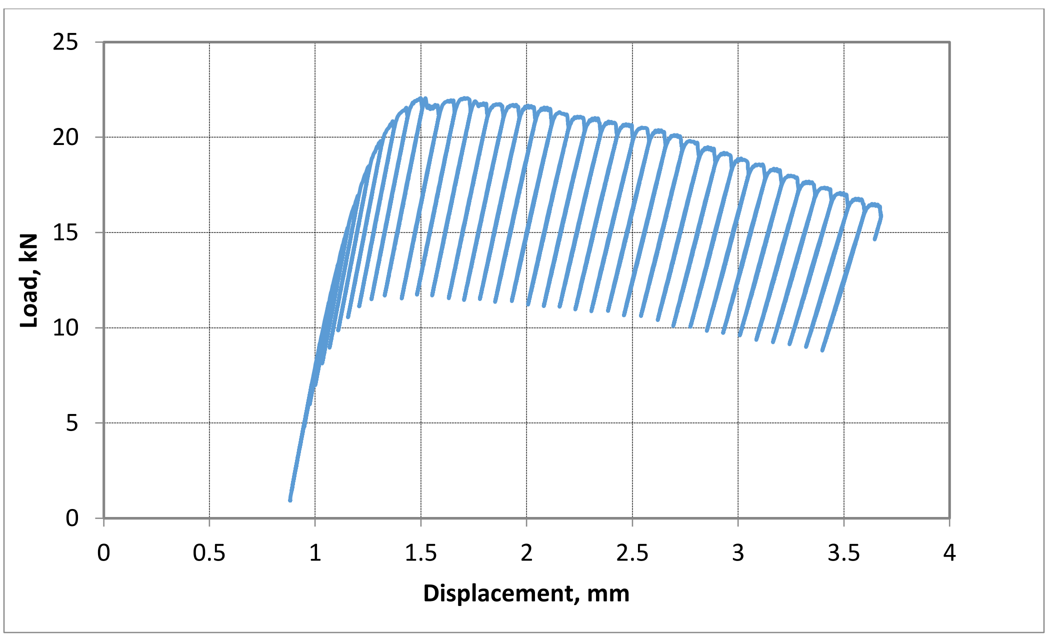


Fig 4.6 Load vs displacement (a/W=0.55 and displacement increment=0.075mm/cycle)

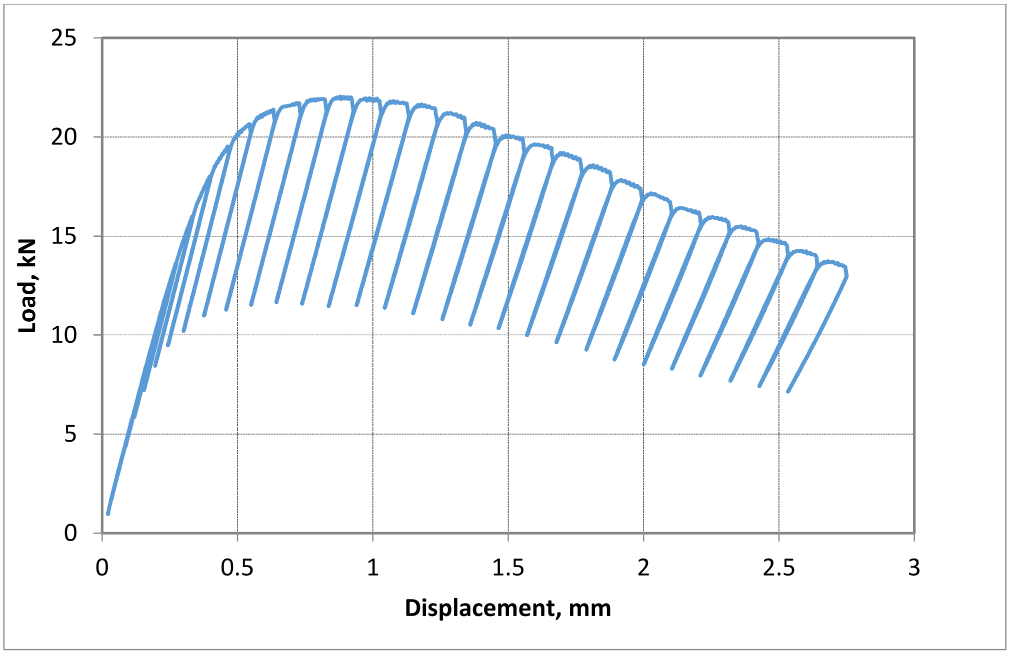


Fig 4.7 Load vs displacement (a/W=0.55 and displacement increment=0.1mm/cycle)

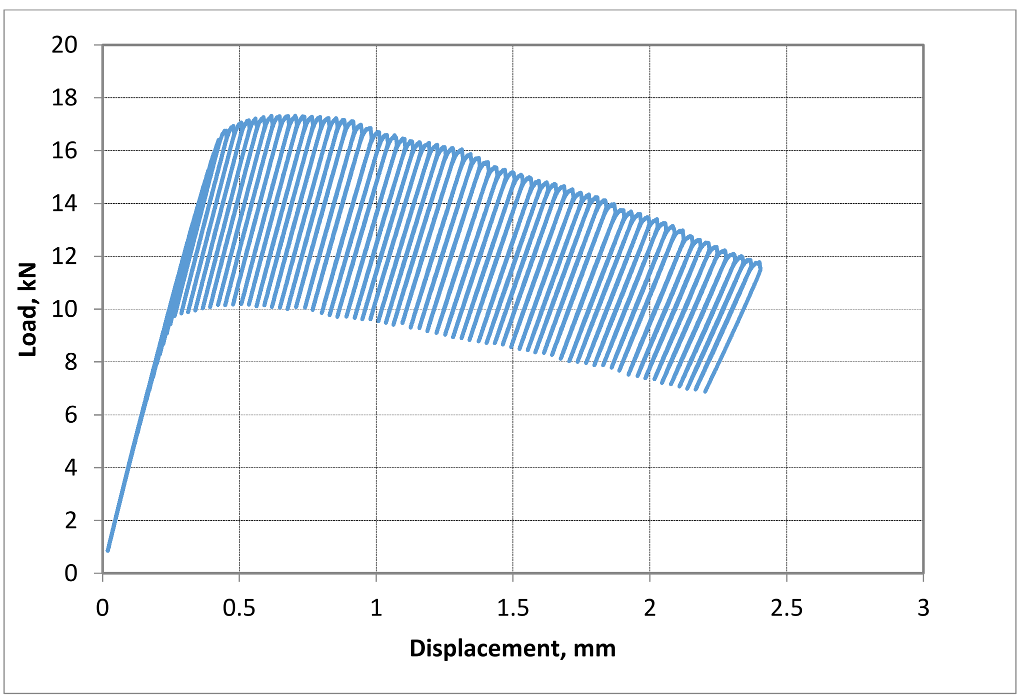


Fig 4.8 Load vs displacement (a/W=0.6 and displacement increment=0.03mm/cycle)

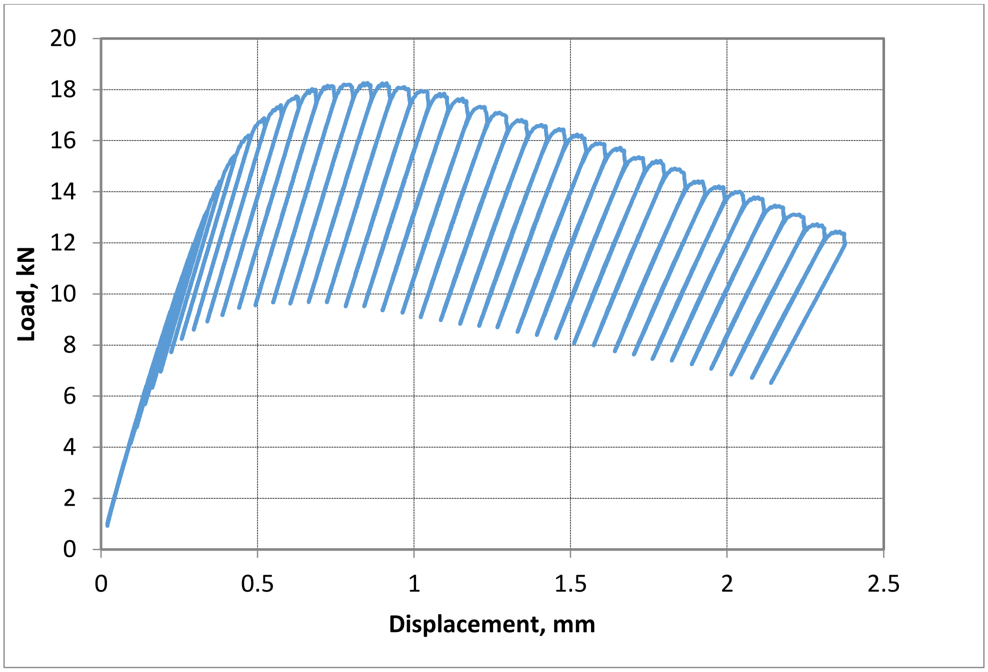


Fig 4.9 Load vs displacement (a/W=0.6 and displacement increment=0.06mm/cycle)

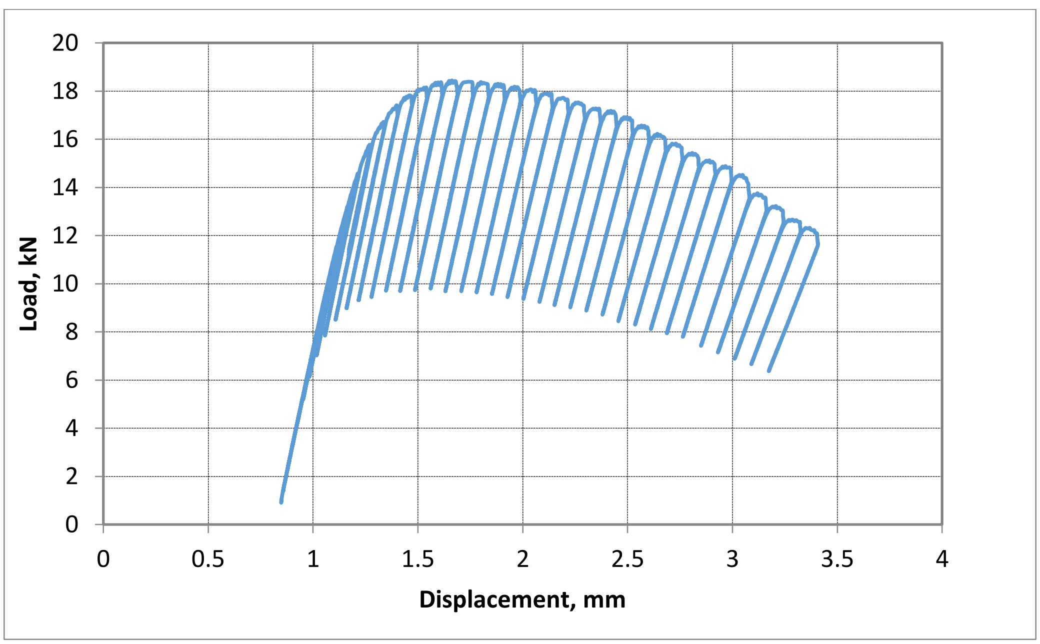


Fig 4.10 Load vs displacement (a/W=0.6 and displacement increment=0.075mm/cycle)

4.3 Data Analysis

The computer controlled Universal Testing Machine gives the value of load and corresponding displacement during the sequential unloading & reloading process of J_{Ic} test. Unloading compliance method is used to calculate J_{Ic}.

Calculation of crack length:

In each cycle the compliance of the unloading path is calculated, taking the points which fall between 40%-90% of the unloading path.

Though the specimen slightly rotates when deforms under the load, the angle of rotation is very small it can be assumed that the corrected compliance is same with the compliance. So $C_{ci}=C_i$.. The crack length (ai) is estimated using the following expression.

$$\frac{a_i}{W} = 1.000196 - 4.06319\mathrm{u}_{(i)} + 11.242\mathrm{u}_{(i)}^2 - 106.043\mathrm{u}_{(i)}^3 + 464.335\mathrm{u}_{(i)}^4 - 650.677\mathrm{u}_{(i)}^5 \quad \text{............. 4.1}$$

$$u_{(i)} = \frac{1}{\left[B_e E C_{c(i)}\right]^{0.5} + 1} \quad \text{............. 4.2}$$

$$B_e = \left[B - \frac{(B - B_N)^2}{B}\right] \quad \text{............. 4.3}$$

Calculation of Ji for corresponding ai:

$$J_i = J_{el(i)} + J_{pl(i)} \quad \text{............. 4.4}$$

Where

$J_{el(i)}$= elastic component of *Ji*

$J_{pl(i)}$= plastic component of *Ji*

Expression for $J_{el(i)}$ is

$$J_{el(i)} = \frac{K^2{}_i(1-v^2)}{E} \quad \text{.......... 4.5}$$

Ki is stress intensity factor

$$K_{(i)} = \frac{P_{(i)}}{(BB_N W)^{0.5}} f\left(\frac{a_i}{W}\right) \quad \text{.......... 4.6}$$

P_i=Maximum load corresponding to crack length a_i

$$f\left(\frac{a_i}{W}\right) = \frac{\left\{\left(2.0+\frac{a_i}{W}\right)\left[0.886+4.640\left(\frac{a_i}{W}\right)-13.320\left(\frac{a_i}{W}\right)^2+14.720\left(\frac{a_i}{W}\right)^3-5.60\left(\frac{a_i}{W}\right)^4\right]\right\}}{\left(1-\frac{a_i}{W}\right)^{1.5}} \quad \text{.... 4.7}$$

Expression for $J_{pl(i)}$:

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{pl(i-1)}}{b_{(i-1)}}\right)\left(\frac{(P_i+P_{(i-1)})(V_{pl(i)}-V_{pl(i-1)})}{2B_N}\right)\right]\left[1-\gamma_{(i-1)}\left(\frac{a_i-a_{(i-1)}}{b_{(i-1)}}\right)\right] \quad \text{..... 4.8}$$

where,

$$\eta_{pl(i)} = 2.0+0.5220\frac{b_{(i-1)}}{W} \quad \text{.......... 4.9}$$

$$\gamma_{(i-1)} = 1.00+0.760\frac{b_{(i-1)}}{W} \quad \text{.......... 4.10}$$

$V_{pl(i)}$ is is plastic portion of LLD and the expression for same is:

$$V_{pl(i)} = V_i - P_i C_{LL(i)} \quad \text{.......... 4.11}$$

where $C_{LL(i)}$ is experimental compliance corresponding to the current crack size.

$$C_{LL(i)} = \frac{1}{EB_e}\left(\frac{W+a_i}{W-a_i}\right)^2\left[2.1630+12.219\left(\frac{a_i}{W}\right)-20.065\left(\frac{a_i}{W}\right)^2-0.9925\left(\frac{a_i}{W}\right)^3+20.609\left(\frac{a_i}{W}\right)^4-9.9314\left(\frac{a_i}{W}\right)^5\right] \quad \text{....... 4.12}$$

Calculation of a_{oq}:

All the Ji and ai pairs from start, till the specimen reached the maximum force are identified. By least square fit procedure, the set of data are used to calculate a_{oq} from following equation.

$$a = aoq + \frac{J}{2\sigma_y} + BJ^2 + CJ^3 \qquad \text{...} \; 4.13$$

where a_{oq} = Provisional crack length

B, C are numerical constants.

After the value of a_{oq} is found, the crack increment at each ai, is calculated, $\Delta\, ai = ai - a_{oq}$ and then J_i vs Δa was plotted. Qualification lines are drawn on it. First among them is the construction line. It was drawn taking first 4 pair of data (J_i and corresponding $\Delta\, ai$). The number of data to be considered for drawing the best fit straight line (construction line/blunting) line is purely arbitrary. This blunting line is then offset three times with 0.15mm, 0,2mm and 1.5mm offset. The minimum exclusion line and maximum exclusion line are the boundary lines and only the points laying in between these lines are to be considered for drawing the regression line. Regression line is the best power curve drawn taking the points between 0.15mm offset line and 1.5 offset line.

Again the blunting line is drawn taking 5 pairs of data, and the same process (from drawing blunting line to the regression line), is repeated. The repetition is done till the slope of blunting line, and power law co-efficient of regression line doesn't change.

The intersection of 0.2mm offset line (also known as the J_Q line) and the regression line (J_R curve) is J_Q (provisional J-integral). Then J_Q is qualified as J_{Ic}, ensuring following condition is satisfied.

$$B, b_0 > \frac{10 J_Q}{\sigma_Y} \qquad \text{...} \; 4.14$$

Figure 4.11 Close- up view of specimen with COD gauge during J_{Ic} test.

The final J_R curves indicating the J_{Ic} values obtained from data analysis of all the tests are given in Fig 4.12 to 4.20.

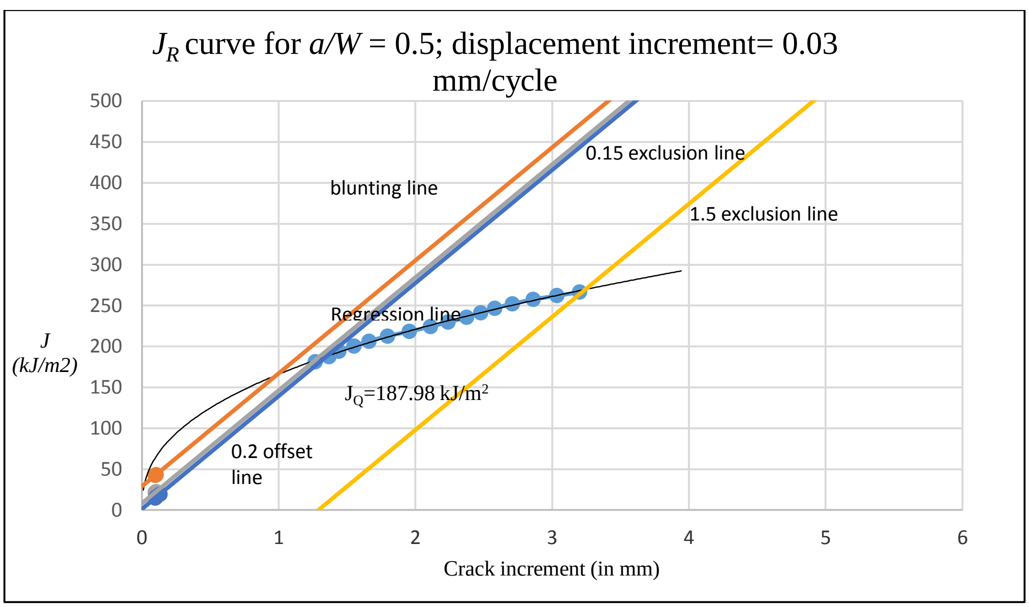


Fig 4.12 J_R curve for a/W = 0.5; displacement increment= 0.03 mm/cycle

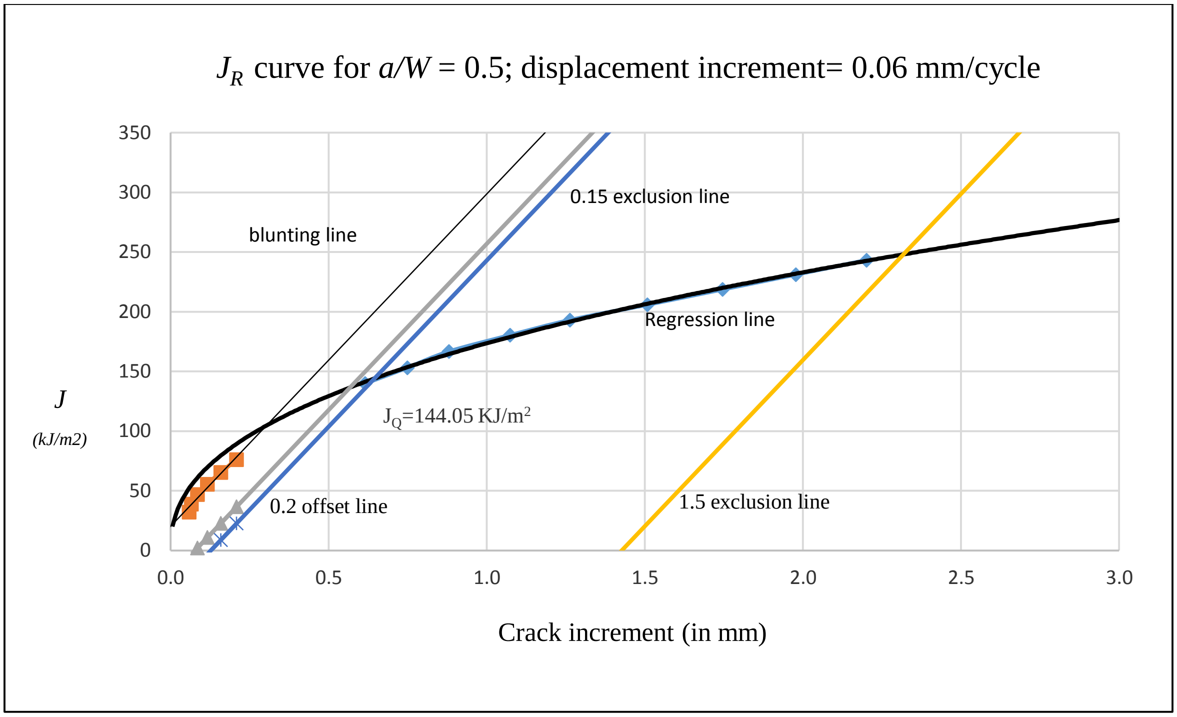


Fig 4.13 J_R curve fora/W = 0.5; displacement increment= 0.06 mm/cycle

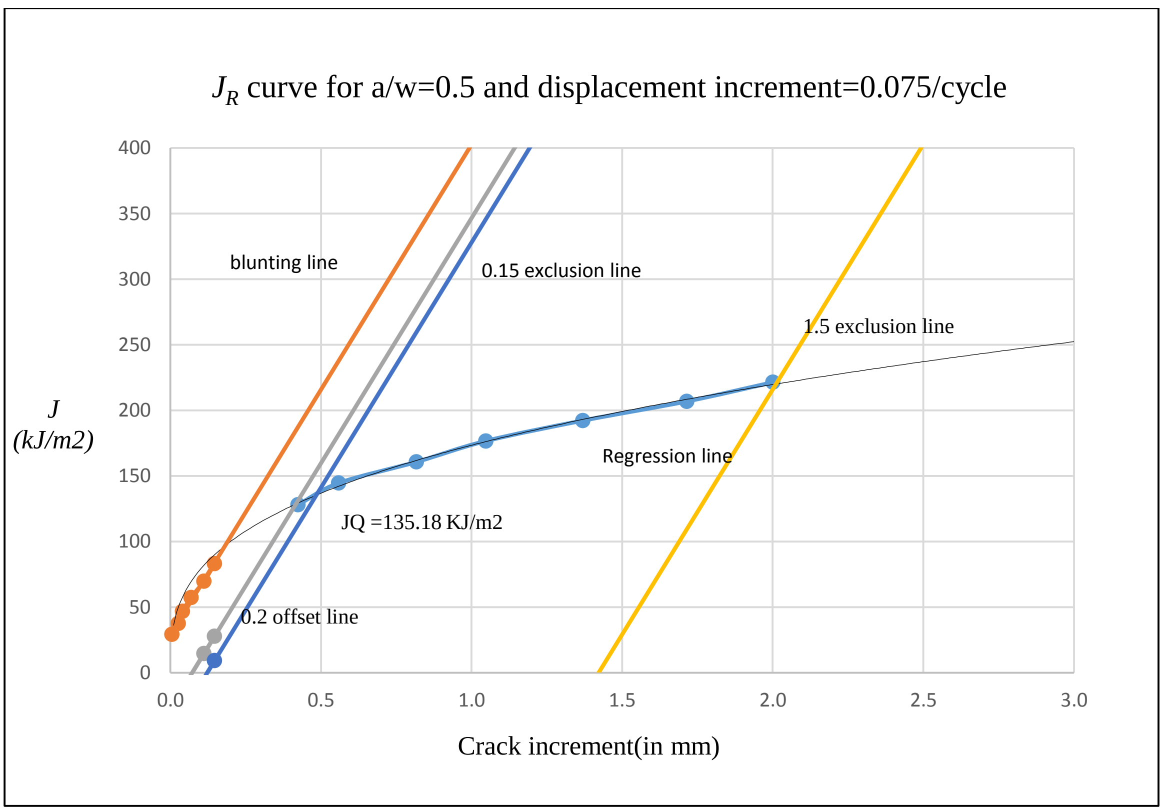


Fig 4.14 J_R curve for a/W=0.5 and displacement increment=0.075/cycle

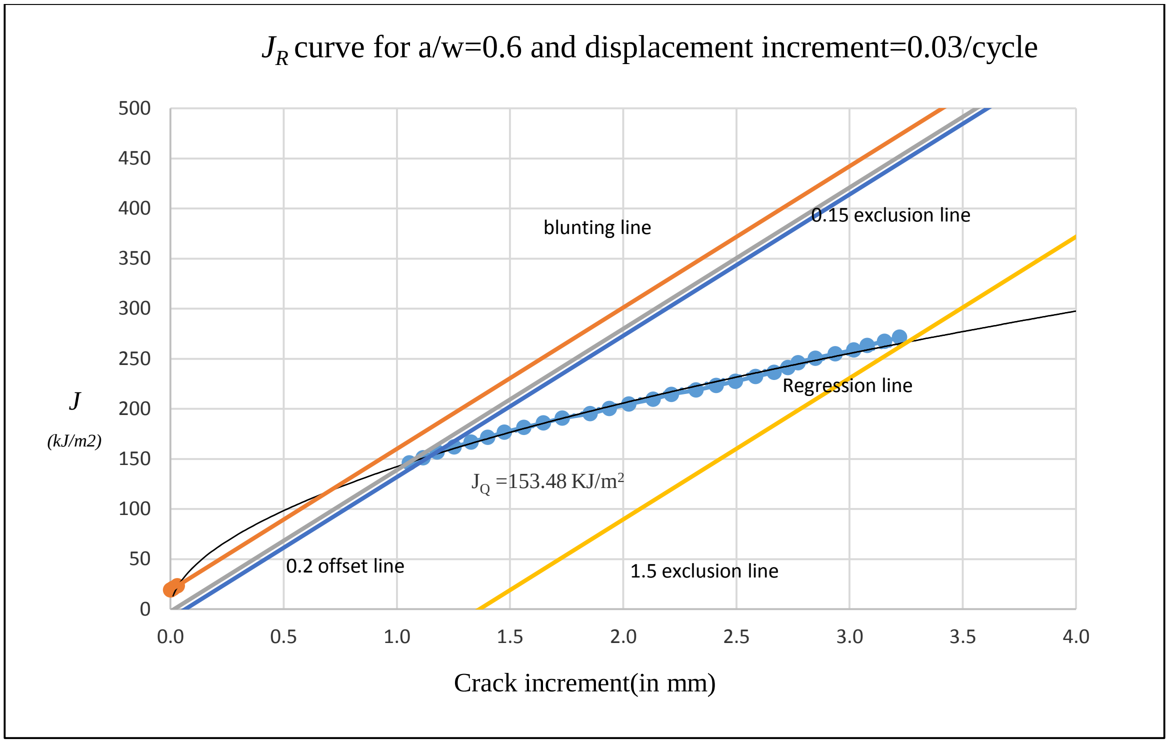


Fig 4.15 J_R curve for a/w=0.6 and displacement increment=0.03/cycle

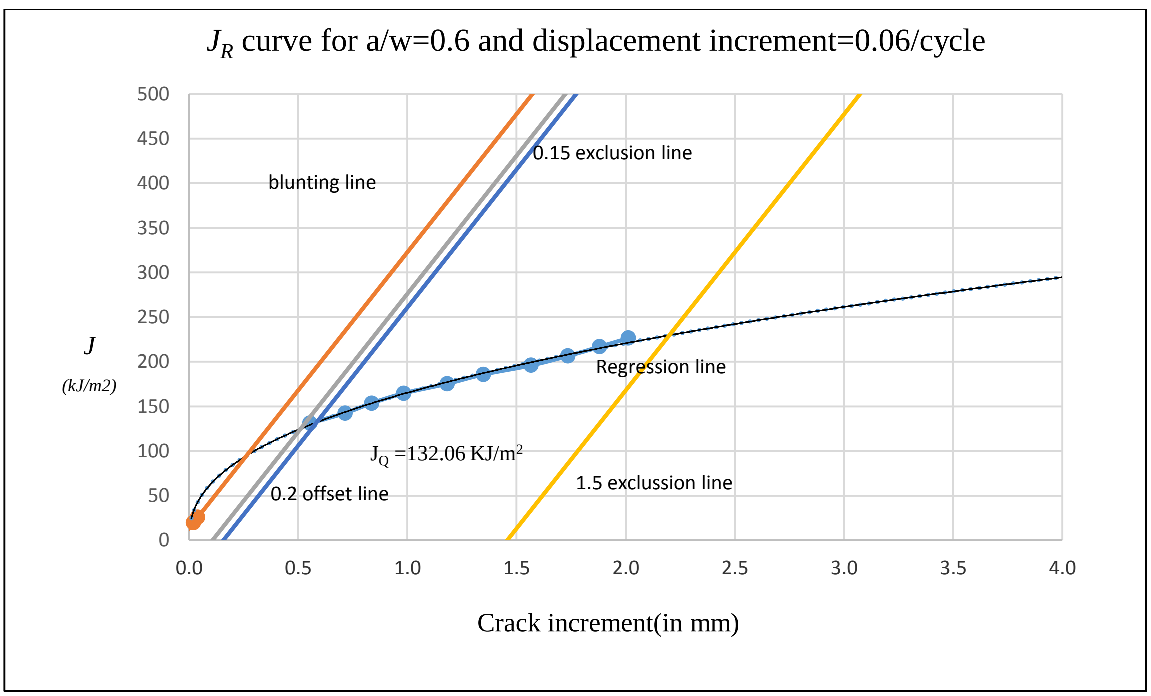


Fig 4.16 J_R curve for a/W=0.6 and displacement increment=0.06/cycle

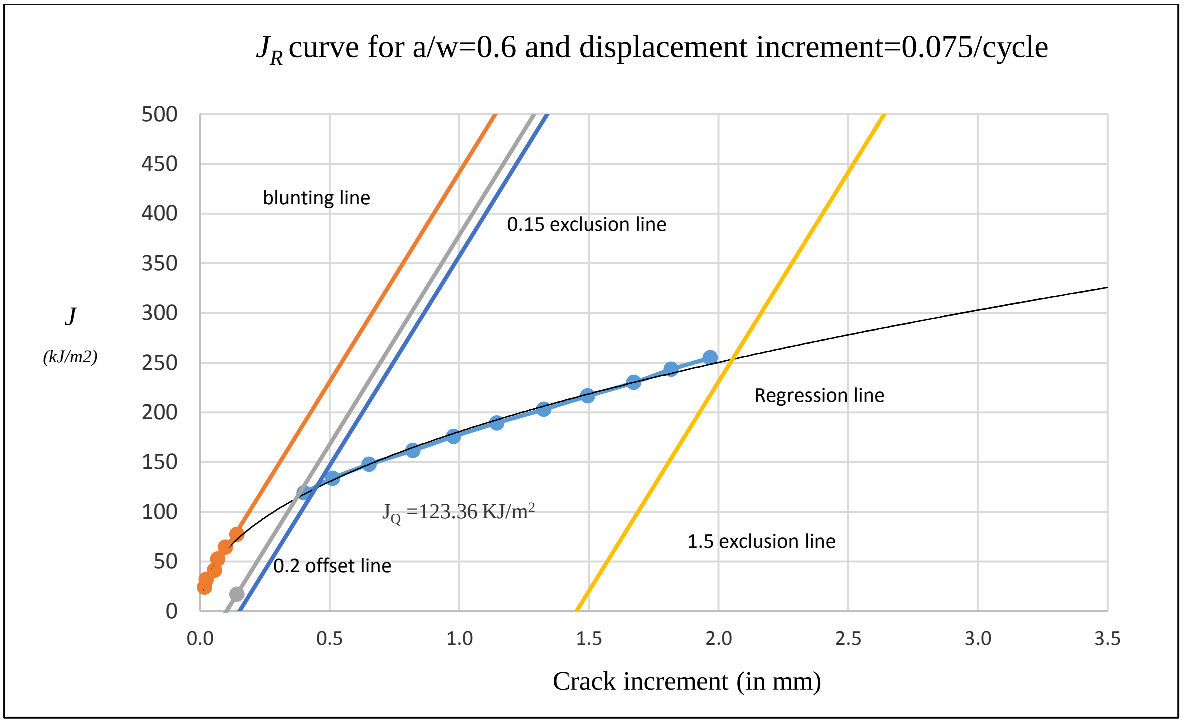


Fig 4.17 J_R curve for a/w=0.6 and displacement increment=0.075/cycle

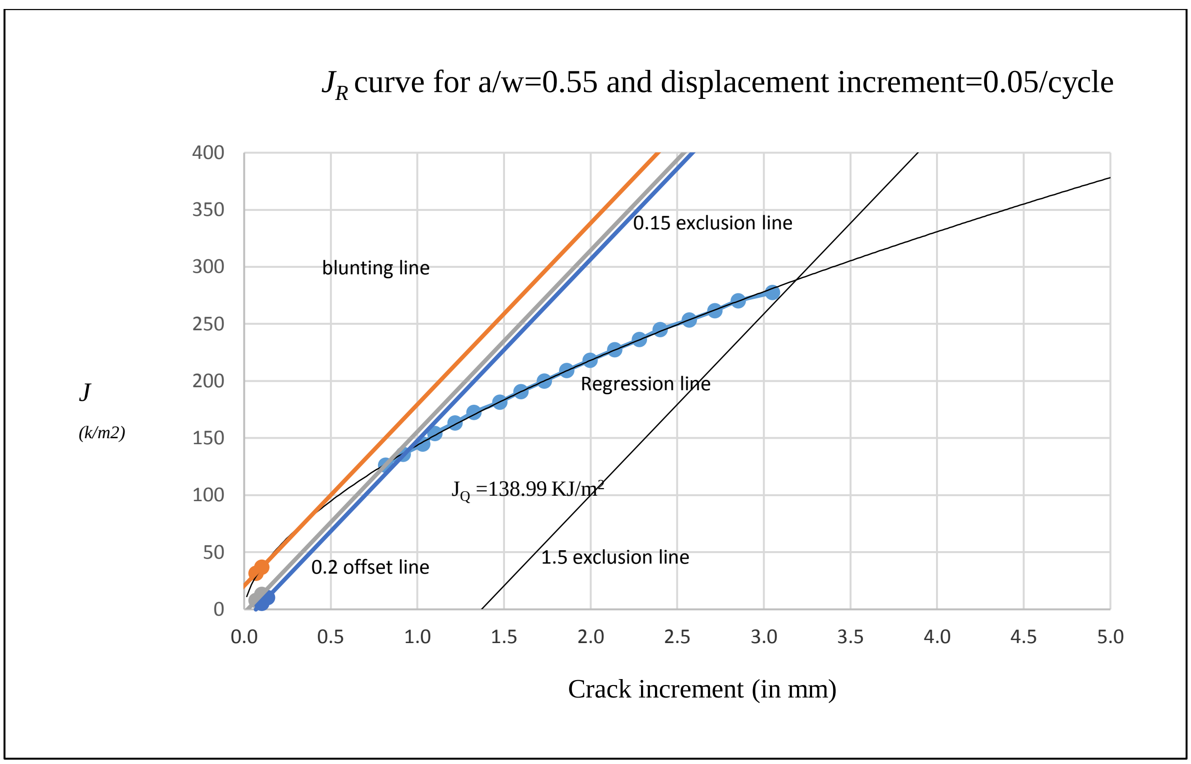


Fig 4.18 J_R curve for a/W=0.55 and displacement increment=0.05/cycle

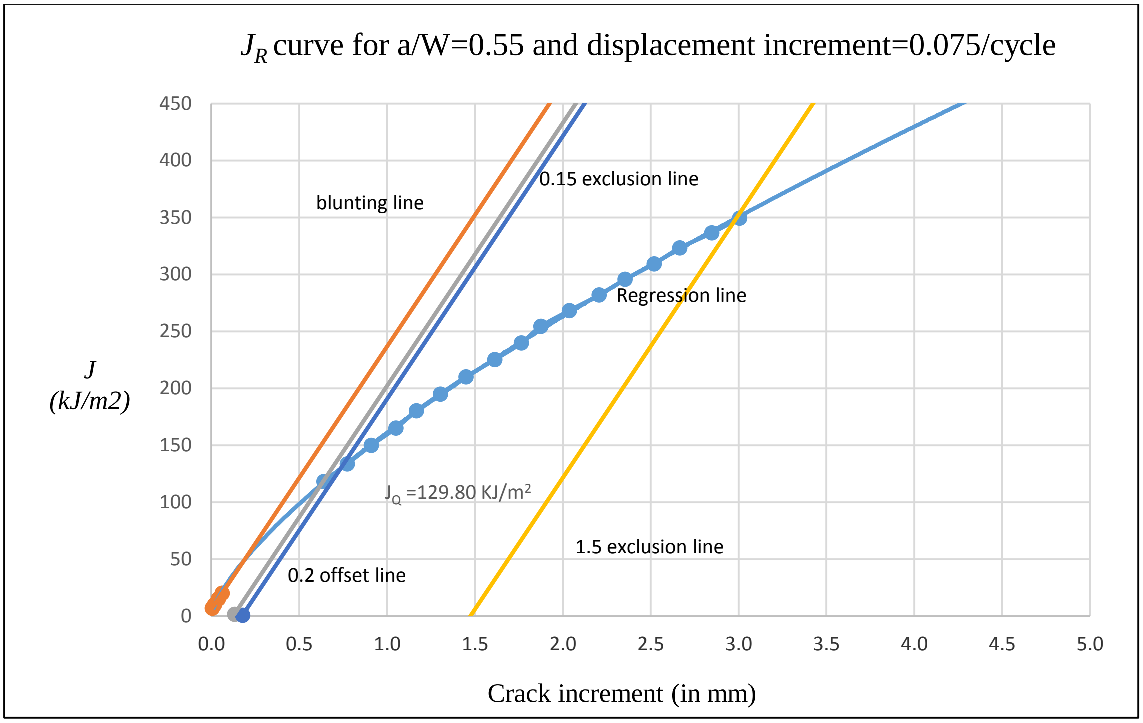


Fig 4.19 J_R curve for a/W=0.55 and displacement increment=0.075/cycle

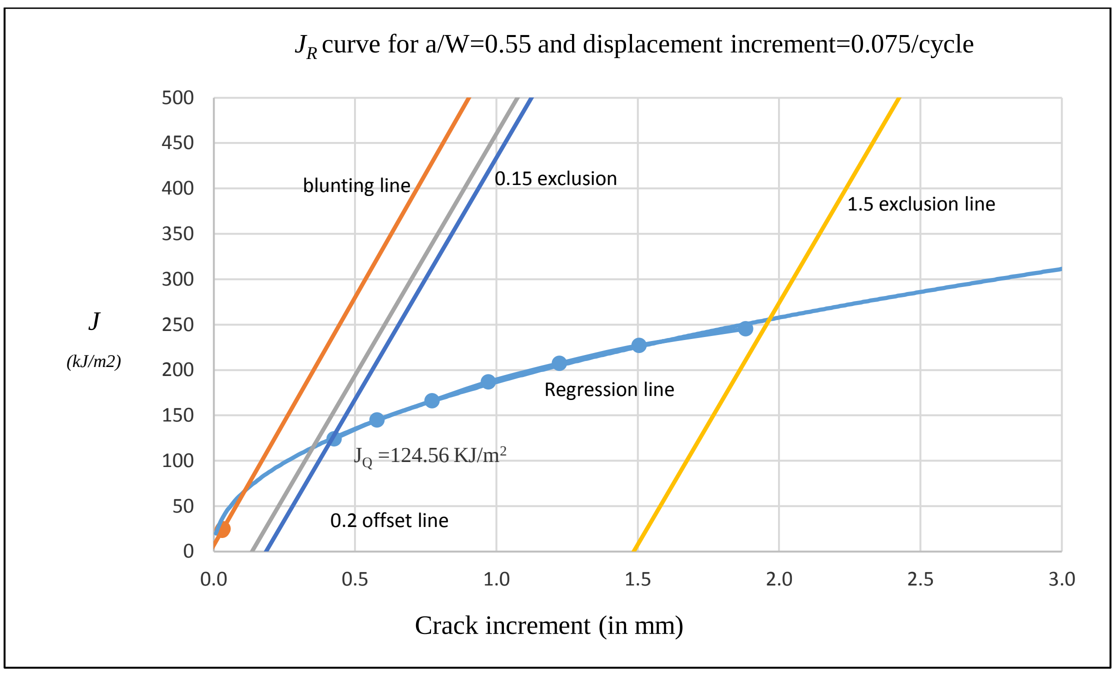


Fig 4.20 J_R curve for a/W=0.55 and displacement increment=0.075/cycle

Chapter-5

RESULTS AND DISCUSSION

5.1 Elastic plastic fracture toughness (J_{Ic})

The value of fracture toughness (J_{Ic}) obtained for various *a/W* ratio (0.5, 0.55, 0.6) and displacement increments (0.03, 0.06, 0.05, 0.075, 0.1), are listed in table4.1 below. The resistance curve procedure which utilizes elastic compliance technique, was used to obtain the fracture toughness (J_{Ic}), in accordance to ASTM 1820.

Table 5.1Value of J_{Ic} for corresponding a/W ratio and displacement increments

Specimen Sr. No	*a/W ratio*	Displacement Increment (mm/cycle)	J_{Ic} (kJ./m^2)	Uncracked Ligament (b_0) (in mm)	Max Limit of Displacement Increment (As per ASTM E1820)
J_{Ic}-1	0.5	0.03	187.98	25.50	0.25
J_{Ic}-2	0.5	0.06	144.05	25.50	0.25
J_{Ic}-3	0.5	0.075	135.18	25.50	0.25
J_{Ic}-4	0.6	0.03	153.48	20.40	0.2
J_{Ic}-5	0.6	0.06	132.06	20.40	0.2
J_{Ic}-6	0.6	0.075	123.36	20.40	0.2
J_{Ic}-7	0.55	0.05	138.99	22.95	0.22
J_{Ic}-8	0.55	0.075	129.80	22.95	0.22
J_{Ic}-9	0.55	0.1	124.56	22.95	0.22

Although in ASTM E1820, the maximum limit of displacement interval/displacement increment between each unload/reload sequence has been mentioned (i.e equal to $0.01*b_0$), it is silent about the lower limit of displacement increment and the effect of displacement increment on value of J_{Ic}. Through this project, it has been tried to investigate how the value of J_{Ic} vary with displacement increment. Using the set of experimental of data as in table 4.1, following forms of equations were tried to obtain a suitable correlation between the three parameters i.e J_{Ic}, a/W ratio and displacement increment.

- $J_{Ic}= A+B(a/W)+Cy+D(a/W)y+E(a/W)^2+Fy^2$
- $J_{Ic}= A (a/W)^{k1} y^{k2}$
- $J_{Ic}^2= (A-By) [C(a/W)^2+ D(a/W)+E]$
- $J_{Ic}= A+B(a/w)y^2+C(a/w)^2y+D(a/W)^3+Ey^3+F(a/W)y+G(a/W)^2+Hy^2+I(a/W)+Jy$

where, $J_{Ic=}$Initiation fracture toughness with Mode-I loading

a/W= Original crack size/Width of the specimen

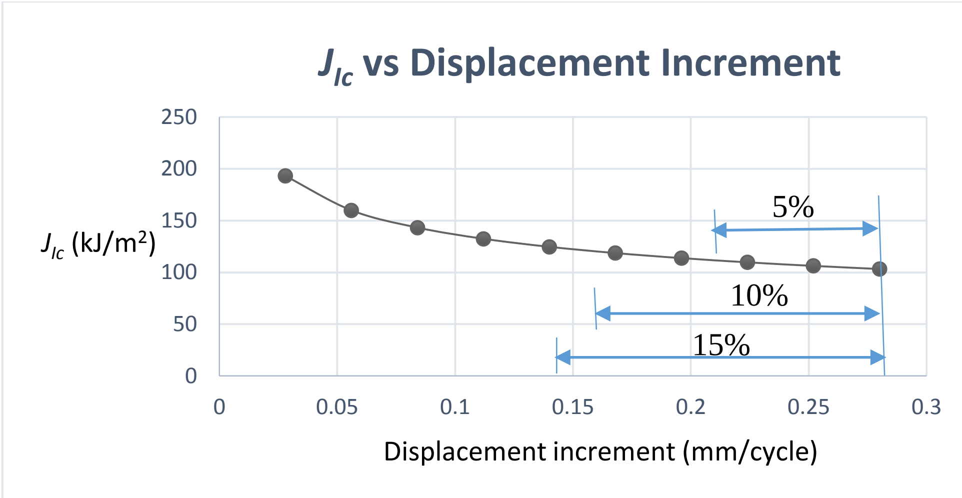
y = displacement increment/displacement interval between each unload/reload sequence

A, B, C, D, E, F, G, H, I, J, K_1, K_2= numerical constant.

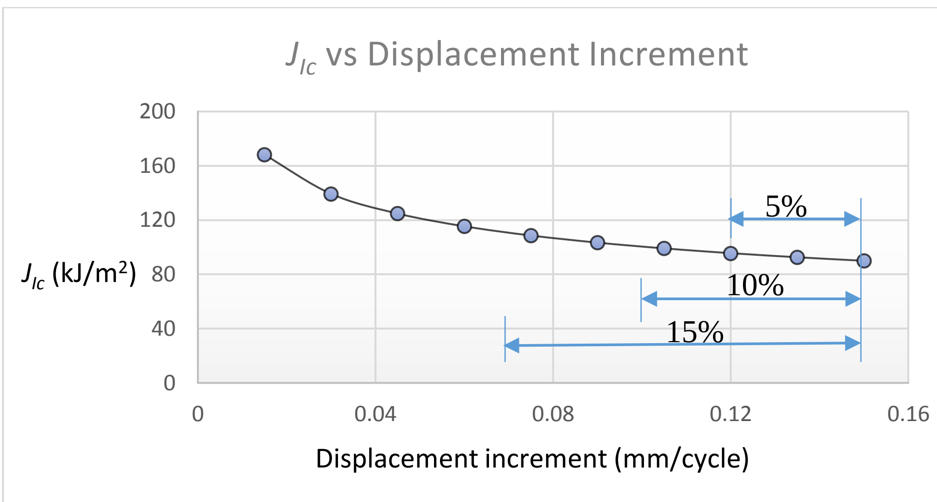
From statistical analysis of the experimental data provided in Table 4.1, it was found that following mathematical equation is best suited to describe the correlation between $J_{Ic,}$ (a/W) ratio and displacement increment(y).

$$\boldsymbol{J_{Ic}= 41.8366(a/W)^{-0.6971}y^{-0.2721}}$$

Using the above equation, effect of displacement increment on value of J_{Ic} at two extreme ends of a/W ratio (0.45 and 0.7) was studied further. Fig-5.1 & 5.2 shows the value of J_{Ic} with increase in displacement increment.



Graph 5.1 J_{Ic} vs Displacement increment (for a/W ratio of 0 .45)



Graph 5.2 J_{Ic} vs Displacement increment (for a/W ratio of 0.7)

It is observed that the fracture toughness (J_{Ic}) increases with decrease in displacement increment. Variation of J_{Ic} (in %) with decrease in displacement increment (in terms of ligament length) is provided in Table 5.2.

5.2 Conclusion

Except the maximum limit of displacement increment in terms of remaining ligament ($0.01*b_0$), ASTM E1820 doesn't specify any range of the displacement increment, for fracture toughness test. From this investigation it has been concluded that, for consistency in fracture toughness value the displacement increment should be kept within the ranges specified in Table 5.2.

Table 5.2 Percentage variation of J_{Ic} with displacement increment

Displacement Increment (in terms of ligament length)	**% variation of J_{Ic}**
(0.008-0.01) b_0	5
(0.006-0.01) b_0	10
(0.005-0.01) b_0	15

where b_0 is the length of un-cracked ligament.

5.3 Scope of future work

1. The observations, got in this research work is valid for HSLA steel only and the variation of fracture toughness with displacement increment for other materials may be considered for future investigation.
2. All the tests were conducted at ambient temperature. It may also be carried out at different range of temperatures.

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